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The environmental and cost performance of current and future motorcycles

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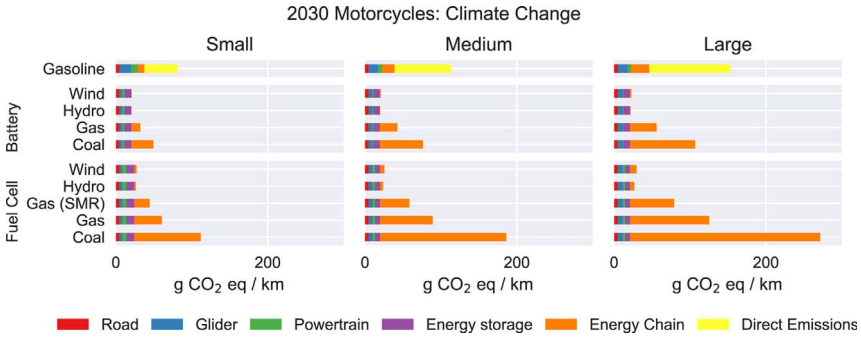
HIGHLIGHTS

- LCA and cost assessment of motorcycles including battery and fuel cell powertrains.
- Battery motorcycles already cost competitive with large environmental benefits.
- Motorcycle environmental performance most strongly dependent on driving speed.
- Extensive supporting information including calculation files and life cycle inventories.

GRAPHICAL ABSTRACT



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ABSTRACT

This work presents an integrative approach to environmental and cost assessment of current and future motorcycle technologies for four motorcycle size categories, three powertrain types, and a variety of fuel supply chains. We consider conventional gasoline (ICEV), battery electric (BEV) and fuel cell electric (FCEV) motorcycles with production years from 1990 to 2030. Motorcycle energy consumption is modelled based on the world harmonized motorcycle test cycle and calibrated with data measured from existing motorcycles. We model the potential future performance of motorcycles by adapting the model input parameters according to historic trends and future component performance predictions. We find that smaller motorcycles have much better environmental performance than larger motorcycles, though this is mostly due to the fact that larger motorcycles have different driving patterns: urban driving is found to have much lower environmental impact per kilometer than highway driving. Current BEV are found to have similar ownership costs to ICEV. They also have reduced climate change potential by roughly 60% when they are powered by electricity from natural gas, 80% when powered by renewables, and they still offer advantages over conventional motorcycles when charged with electricity from hard coal. Next generation BEV are found to have similar environmental performance advantages, though with a definite cost advantage. FCEV climate change reduction potential is found to depend strongly on the source of the hydrogen fuel, with climate benefits being substantial with hydrogen originating from renewable energy sources. Future cost competitiveness of FCEVs is linked closely to the development of fuel cell costs.

1. Introduction

Motorcycles and scooters (hereafter referred to as motorcycles) typically have lower operating costs and fuel consumption than passenger cars and contribute less to traffic congestion while still providing the personal freedom that is not available with public transportation. For these reasons, motorcycles are viewed as a technology with the potential to reduce the impacts of passenger transportation, especially in

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urban areas [1–3]. In some countries, such as Vietnam, India, Indonesia, Thailand, Taiwan, and China, motorcycles make up over 60% of the passenger vehicle fleet [4]. Although they offer benefits in terms of energy consumption compared to cars, combustion motorcycles have also been shown to cause significant emissions of many air pollutants responsible for public health problems [5–7]. However, motorcycle tailpipe emissions have decreased drastically in the past two decades and are expected to continue to do so in the near future [8–10].

Advanced technologies such as electric powertrains may have the potential to further reduce motorcycle energy consumption and greenhouse gas (GHG) emissions while nearly eliminating the impact of motorcycle travel on urban air quality [3,11]. Advanced powertrain motorcycles have rapidly gained in popularity in recent years, and there are already several manufacturers offering battery electric motorcycles in all size categories [12–21]. Moreover, several concepts for fuel cell electric motorcycles have been published to date [22–24]. While advanced powertrain motorcycles have no direct tailpipe emissions and thus perform well in terms of direct urban air pollution, the environmental impacts of producing the motorcycle and the electricity or hydrogen used to power it can be significant from a life cycle assessment perspective [3,11,25].

It seems likely that motorcycles will play a role in future urban transport solutions, though their environmental benefits are strongly dependent on powertrain type, energy chain and motorcycle size. Thus, decision makers and modelers require more information regarding the environmental performance and costs of different types of future motorcycles. Ideally, this information should be life cycle based to allow a complete comparison of the powertrain types and avoid burden shifting. It should also include variations in key performance parameters such as motorcycle size and fuel production chains. The goal of this paper is to provide this information using a consistent framework and a neutral technology point of view.

1.1. Previous work

There are several excellent resources available that tabulate the fuel consumption and exhaust emissions of internal combustion motorcycles, often including different motorcycle sizes, driving patterns, and emission standards [10,26–28]. These sources show that motorcycle emissions and fuel consumption are strongly dependent on motorcycle size and production year (indicated by Euro category). However, these studies consider only conventional motorcycles and do not include the whole life cycle of the motorcycle or cost information.

A number of studies do consider motorcycles with battery or fuel cell electric powertrains, and some even perform LCA of these motorcycles and compare them to conventional motorcycles [3,11,25,29–33]: Cherry et al. [33] examined lead battery based electric bicycles in China and compared them to competing modes of transport, such as conventional bicycles, motorcycles, cars and buses. Del Duce and Gauch [11] evaluated the environmental impacts of different transport technologies for Swiss Post and included combustion and electric scooters in their analysis. Leuenberger and Frischknecht [31] created detailed datasets for electric and combustion scooters which are now included in the ecoinvent database. Hofmann et al. [29] analyzed the potential of small electric cars and scooters for the Swiss Federal Office of Energy in 2013. They based their life cycle inventories for motorcycle production on ecoinvent, but carried out detailed measurements and modelling of electric scooter energy consumption. Hwang and Chang [30] studied the well-to-wheel greenhouse gas emissions from combustion, fuel cell and battery scooters. Walker and Roser [32] modelled cost and energy consumption of gasoline, battery electric and hybrid motorcycles. Mellino and Petrillo [25] performed LCA comparing battery and fuel cell electric bicycles to a conventional scooter. Weiss and Dekker [3] consider the life cycle environmental impacts of several size classes of electric motorcycles and compare them to bicycles, motorcycles, passenger cars and buses, also including cost information.

In general, these studies find that electric and fuel cell powered motorcycles have higher tank-to-wheel efficiencies than combustion motorcycles and thus have the potential to reduce greenhouse gas emissions. The energy consumption values for motorcycles are rather consistent across all studies, though they vary significantly according to motorcycle size. Life cycle impacts per kilometer (where reported) are found to vary, mostly due to differences in assumptions regarding the lifetime distance travelled and the source of electricity and hydrogen. This makes it very difficult to draw general conclusions about the performance of different motorcycle powertrains and sizes. Furthermore, as all of these technologies seem to be improving quite rapidly due to emission standards for conventional motorcycles and battery and fuel cell technology development for advanced powertrains, it is highly unclear how these technologies might compare in the mid-term future, which is the time horizon of interest for decision makers. Finally, it seems that all of the above studies that considered lithium ion battery based electric bicycles and motorcycles in their assessment used the lithium ion battery life cycle inventory from the ecoinvent database, which in turn is taken from Notter and Gauch [34]. However, the energy consumption assumptions for battery production contained therein are very optimistic, likely leading to an underestimation of the impacts of producing lithium ion batteries in these studies [35,36].

1.2. Research goals

Although many conclusions may be drawn from the studies discussed above, we feel that the literature still lacks a single study that considers the environmental and cost performance of all relevant motorcycle powertrain types and sizes, a wider selection of energy production chains, as well as past, current, and future technology performance. We provide a comparison of the cost and environmental performance of both conventional (gasoline combustion) and advanced powertrain (battery electric and fuel cell electric) motorcycles. We believe that such a comparison will not only be of use to persons interested in purchasing a motorcycle, but also helpful for decision makers and model developers in the areas of energy and transport. To this end, we also provide model results for historic motorcycles starting with production year 1990, and future motorcycles with production year 2030. We include four different motorcycle sizes in order to better understand the impact that size has on the cost of a motorcycle and its environmental performance. We focus on motorcycles produced globally, but operated in Western Europe.

As our goal is to provide input information for decision makers and modelers, we also include all calculation files, input assumptions, and results in supporting information (SI) so that others may build on our work. We hope that our results will be used to more accurately include different motorcycle sizes and powertrains in transportation, economic and energy models as well as life cycle databases.

2. Methods and calculation

2.1. Motorcycles considered

This study models the environmental and cost performance of internal combustion (ICEV), battery electric (BEV) and fuel cell electric (FCEV) motorcycles. Four different motorcycle size classes that represent the entire range of motorcycles commonly found in the fleet are included (see Table 1). ICEV motorcycles are modelled for production years 1990–2030, while BEV and FCEV motorcycles are modelled for production years 2015–2030. We include FCEV motorcycles in the base year of 2015 to represent their performance as if they had been commercially produced, thus allowing their comparison with other motorcycle types.[1] However, it seems unlikely that fuel cell powered motorcycles will be common before 2020.

Table 1
Summary of motorcycle characteristics. Values apply to all motorcycle production years.

Power (kW)	Powertrain	Lifetime (years)	Annual Distance (km)	Range (km)	Driving Cycle (WMTC)
4	ICEV	12	2400	250	1.2
	FCEV	12	2400	250	1.2
	BEV	12	2400	80	1.2
11	ICEV	15	4600	250	2.1
	FCEV	15	4600	250	2.1
	BEV	15	4600	100	2.1
25	ICEV	20	5700	300	3.1
	FCEV	20	5700	300	3.1
	BEV	20	5700	120	3.1
50	ICEV	25	5800	350	3.2
	FCEV	25	5800	350	3.2
	BEV	25	5800	150	3.2

2.2. Life cycle assessment

Life Cycle Assessment (LCA) is a method that can be used to compare the total environmental impacts of different products or services. The goal of LCA is to include all environmentally relevant flows of a product or service over its entire life cycle (from resource extraction through operation to end of life) by gathering a Life Cycle Inventory (LCI). The potential environmental burdens from these flows are then calculated using Life Cycle Impact Assessment (LCIA) [37].

We use LCA to compare the driving of different motorcycles for one kilometer, averaged over the entire vehicle lifetime, which is the functional unit of our study. The system boundary is defined as cradle-to-grave and includes both the equipment life cycle as well as the well-to-wheel fuel chain. We use ecoinvent v3.2 with the recycled content approach and attributional system model as a background database and make the simplifying assumption that it is valid for use for 1990 and 2030 production chains.

We perform LCIA using the ReCiPe 2008 method with the hierarchist perspective [38]. We include all ReCiPe midpoint and endpoint indicators in SI, though in the main body of the paper we select the three midpoint indicators that we feel are most relevant for motorcycle transportation:

Climate Change (CC) represents the contribution to climate change due to the emission of greenhouse gases such as CO_2 and CH_4. For this indicator we have selected the most recent global warming potential characterization factors from the IPCC as implemented by the ecoinvent Centre [39,40]. CC is quantified in kg CO_2 equivalent.

Particulate Matter Formation (PMF) considers the human health impacts of fine particles in the air that can enter the lungs. The method takes into account not only the direct emission of particulates, but also the formation of secondary particulates due to emissions such SO_x, NO_x, and ammonia (NH_3). PMF is quantified in kg PM 10 equivalent.

Photochemical Oxidant Formation (POF) considers the formation of ground level ozone due to the reaction of NO_x with Non Methane Volatile Organic Compounds (NMVOCs). POF is quantified in kg NMVOC equivalent.

2.3. Life cycle costing

We model the life cycle costs of motorcycle travel according to the owner's perspective with a discount rate of 5% and present results in 2015 US dollars. Cost input data are taken from current consumer prices where available and estimated from literature where reliable pricing information could not be found. Where only manufacturing costs are available in the literature, we assume that the cost for consumers is double the manufacturing cost. This assumption seems to hold true for lithium ion batteries: they currently incur manufacturing costs on the order of 300–400 $/kW h [41], while consumers may purchase them as upgrade packages from motorcycle manufacturers at roughly double this amount [13,19,20]. The most important cost assumptions are listed in the following sections; all assumptions are defined in SI.

[1] When calculating the costs of current FCEV, we consider costs as if the motorcycles were currently produced on a significant scale similar to BEV, not the costs of a prototype. However, we use current fuel cell costs for the production levels that are currently common and not future, large scale mass production costs.

2.4. Modelling approach

In order to ensure fair comparison between different motorcycles, an approach similar to that adopted in the recently completed research project THELMA is used [42,43]. In this approach, all motorcycle types are modelled using the same basic framework and only the components related to the different powertrains differ, meaning the glider, power, lifetime, and driving characteristics are held constant for all powertrain types. It should be noted that an exception is made for range; it is not constant for all motorcycle types, but rather is reduced for BEVs. However, the range assumptions made here correspond quite well to the ranges of current commercial BEV [12–20]. Based on these basic parameters, which are the same for all motorcycles of each size category and year, the sizes and costs of all components as well as motorcycle energy consumption are calculated. These results are then linked with the ecoinvent database to calculate the life cycle impact assessment results. The most important aspects of this calculation procedure are detailed in the following sections. Furthermore, the complete calculation and results are available as jupyter notebooks in SI. The modelling framework is depicted in Fig. 1.

2.5. Motorcycle use parameters

This section describes the operational characteristics of the motorcycles included in this analysis, summarized in Table 1. The lifetime distance travelled by a motorcycle is an important parameter for the calculation of its life cycle impacts and costs. However, this parameter is also highly uncertain: While the TREMOVE database assumes that all motorcycles have an average operating lifetime of 25 years, our analysis of Swiss motorcycle stock statistics from 1990 to 2014 shows that smaller motorcycles tend to remain in the fleet for only 10–12 years on average [44,45]. The European average for each size class is taken as the annual distance travelled. For small motorcycles, this is commonly between 2000 and 5000 km/year and for large motorcycles 4000–6000 km/year [27,46]. However, this value can vary greatly and may even be on the order of 10,000–20,000 km per year, as seen in data from the Swiss mobility census results for 2009 [47]. For this analysis, we consider typical operation patterns and include motorcycle lifetime kilometers driven in the sensitivity analysis, which can be found in SI.

We assume that all motorcycle components have the same lifetime as the motorcycle. While a 25 year lifetime seems to be very high for a fuel cell or lithium battery, the rather short distance travelled per year means that the lifetime distance travelled is still below 150,000 km even for the largest motorcycle size class, which is a comparatively low value for passenger cars [42]. Furthermore, the total number of battery cycles remains below 1000 and the total hours on the fuel cell below 3000, which are reasonable expectations for today's components. Walker and Roser [32] also calculate that even when discharging the battery fully in each cycle, its end of life is not reached at the end of the electric motorcycle's lifetime. In the sensitivity analysis, we include a scenario where the battery and fuel cell are replaced once during the motorcycle lifetime.

Motorcycle driving characteristics are taken from the World Harmonized Motorcycle Test Cycle (WMTC) [46]. This test is broken into three main sections corresponding to urban, rural, and highway driving. The smallest motorcycle size classes are only required to be

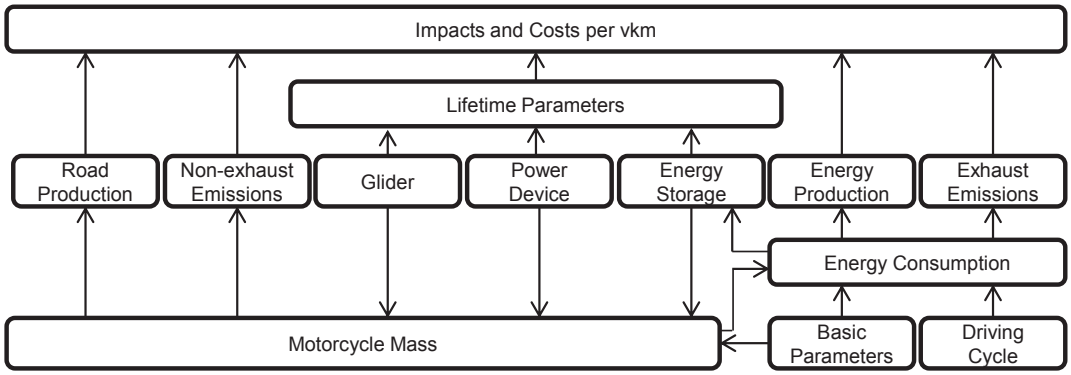

Fig. 1. Schematic of modelling framework.

tested on the urban section (Sections 1.1,1.2 and 1.3). Medium sized motorcycles are tested on the urban and rural sections (Sections 2.1–2.2) while the largest motorcycles are subjected to all three sections of the test (Sections 3.1–3.2). The WMTC is further examined in Section 2.7 below, where we discuss motorcycle energy consumption. We perform all calculations assuming one 80 kg rider is on the motorcycle. We vary this value between 60 kg and 160 kg in the sensitivity analysis.

2.6. Motorcycle characterization

In this model, motorcycles are considered to be composed of a glider, a power device and an energy storage device. The sizes of all components are calculated based on the input values in Table 1. When calculating the masses of each component, we use simple linear and exponential continuous functions as opposed to discrete values so that the model is capable of calculating results for motorcycles of all sizes and production years. We define these functions based on curves fitted to data gathered from commercial motorcycle components, using our own judgement where detailed data is not available and the component is not critical to the results. Furthermore, many components are assumed to improve over time. To account for this, we use 2015 as the base year and assume annual improvements based on available literature, manufacturer information, historical data and, where no other data is available, expert judgement. In order to confirm the validity of input values, motorcycle mass and energy consumption results are compared and calibrated using values from commercially available motorcycles in SI, showing good results.

We briefly describe all major components in the paragraphs below. Detailed characterization of each motorcycle is included in SI. As the performance assumptions for batteries, fuel cells and hydrogen storage are critical to our results, we include them in Table 2.

2.6.1. Glider

The glider is defined as all parts of the motorcycle that are not part of the powertrain or energy storage, i.e. the frame, wheels, brakes, seat, etc. Glider mass is determined by analyzing the weight and power of over 7000 production motorcycles and subtracting the calculated mass of the powertrain components [79]. The material composition, construction data and disposal datasets for the glider are scaled linearly by mass based on datasets for motorcycle production and disposal in the ecoinvent 3.2 database, which are themselves adapted from data for car manufacture to match motorcycle material compositions. These datasets show that motorcycle gliders are composed primarily of steel (55%), plastic (26%), aluminum (16%) and synthetic rubber (3%). Our analysis of commercial motorcycles shows that glider mass has remained roughly constant for the past decades. Therefore, we assume no weight reductions and no changes in material composition for future motorcycle gliders. While the weights of high-performance motorcycles have been reduced over time due to design refinements and advanced materials such as carbon fiber, we are concerned with average motorcycles, which have not changed significantly over time. Costs for motorcycle gliders are inferred from purchase costs for common motorcycles [3,12,13,16,18–20,80].

Motorcycle glider maintenance includes replacement tires, brakes and some steel, aluminum and plastic to represent replacement parts based on data from Leuenberger and Frischknecht [31] and the ecoinvent database, scaled by motorcycle weight. Costs for motorcycle maintenance are assumed to be 3% of the glider cost annually for ICEV and FCEV and only 2.5% of the glider costs for BEV due to their simplified powertrain [29,32].

2.6.2. ICEV powertrain

The LCI for the internal combustion engine (ICE) and transmission assembly are downscaled using ecoinvent inventories for the production of passenger car engines. The gasoline tank is assumed to be manufactured from high density polyethylene. The weights and costs of these components are calculated using data found online [71,79,80]. Costs for the combustion engine are expected to slightly increase in the future due to increasingly strict emission limits and efficiency requirements [43].

2.6.3. Electric motor

Electric motors are assumed to be brushless DC motors connected to the drive wheel by a belt. LCI data for the electric powertrain (electric motor and controller) are taken from the ecoinvent 3.2 database and scaled by component mass. The materials used in these components and their manufacture are assumed to remain constant over time. Costs and masses for electric motors are taken from project THELMA, though modified to consider the smaller sizes required for motorcycles based on manufacturer information [43,57–59,71].

2.6.4. Lithium ion batteries

Energy storage and power regulation is assumed to rely on lithium ion batteries. We convert energy to power values using a discharge rate of 10 C, which is a typical value for lithium batteries for hybrid vehicles. For 2015 battery system performance, we assume 140 W h/kg and increase this value to 250 W h/kg in 2030, which corresponds to a cell level energy density of 350–400 Wh/kg and is in line with US DOE targets and predictions by battery experts for the mid-2020s [68–70].

For battery manufacture costs, we assume 350 $/kW h in 2015, decreasing to 150 $/kW h by 2030 [41,68,69], resulting in current and future consumer purchase costs of 700 and 300 $/kW h, respectively. An 80% depth of discharge is used for battery sizing and range calculation.

LCI data for the lithium ion battery production are taken from Ellingsen and Majeau-Bettez [81], with the ratio of the battery cell adjusted to make up 70% of the battery mass to compensate for the comparatively simple balance of plant required for motorcycles compared to passenger cars. We use a battery production energy value of 24 kW h/kg battery cell, which seems to be in line with the most current

Table 2
Summary performance parameters.

	2015	2030	Units	Source/comment
TtW efficiency				
ICEV	14.5%	15.4%		Calibrated based on: [5,10,27,29,43,48–56]
BEV	81.0%	83.5%		Calculated using: [11,13,15,17,19–20,29,31,32,57–60]
FCEV	39.6%	45.4%		Calculated using BEV values and: [11,42,61–67]
Lithium ion batteries				
Energy density	140	250	W h/kg	[19–20,41–43,62,68–70]
Manufacture cost	350	150	$/kW h	[41,43,60,71]
Consumer price	700	300	$/kW h	[12,13,19,20,32,43,60,71]
Discharge rate	10 C	10 C	kW/kW h	Typical value
PEM fuel cell				
Share of peak power	50%	50%		Minimize fuel cell size, but meet baseload power requirements
Share of baseload energy	100%	100%		Plug-in hybrid not considered
Stack power density	1.95	2.44	kW/kg	Values based on: [43,61–65,72]
Cell power area density	0.83	1.04	W/cm^2	Values based on: [43,61–64,72]
Platinum loading	0.151	0.12	g/kW gross	Values based on: [43,61–64,72]
Essential BoP mass	0.33/10	0.26/8	kg/kW/kg fixed	Values based on: [43,61–65,72] Maximally compact design
Ancillary BoP mass	0.4	0.32	kg/kW	Values based on: [43,61–65,72]
Average system efficiency	48.9%	54%		Values based on: [43,61–64,72]
Manufacture cost	230	60	$/kW	[43,62,63,66,73]
Consumer price	460	120	$/kW	Rough estimate based on prices of fuel cell cars [72,74]
Hydrogen tank				
Storage pressure	700	700	bar	Typical value
Hydrogen storage efficiency	5%	7%		[72,75–78]
Manufacture cost	25	17	$/kW h	[75,78]
Consumer price	50	34	$/kW h	Rough estimate (2× manufacturing cost)

literature [35,36,82,83]. This energy consumption is the driving factor of the environmental burdens of lithium ion battery production, as it is predominantly caused by the climate control requirements of the clean room for cell production [81]. For this reason, we assume that the production impacts of batteries scale with the mass of the battery rather than with energy storage capacity. We further assume that the production processes for and material composition of future batteries are similar to current batteries. We consider this to be a reasonable approach as the majority of impacts from lithium battery production are due to the electricity consumed during battery production and the material used for the current collectors and are rather independent of battery chemistry itself [36,81].

2.6.5. PEM fuel cell

FCEV motorcycles are modelled as hybrids and are assumed to use lithium ion power batteries to provide 50% of the peak power and a Polymer Electrolyte Membrane (PEM) fuel cell to provide base load energy and 50% of the peak power. We do not consider the potential to recharge these batteries from the grid.

We take our model of a PEM fuel cell from the inventory and performance described in Simons and Bauer [61]. We find that Simons and Bauer's 2020 fuel cell corresponds quite well to current fuel cell performance and thus use their values as our baseline. Current fuel cell stack performance is set to 1.95 kW/kg, 0.83 W/cm^2 and average system efficiency to 48.9%. Platinum loading is 0.151 g/kW. This agrees quite well with other available performance data for 2015 fuel cells [62–64]. Although these sources consider larger fuel cells to be used in cars, this power density is also feasible for small stacks: For example, Intelligent Energy now offers a lightweight version of their AC64 stacks with a similar power density starting at 1 kW [65].

We estimate the future performance of fuel cell stacks by modifying the cell power area density and efficiency parameters of our model for current stacks. For 2030 cells, we assume that the power area density will increase to 1.04 W/cm^2 and system efficiency to 54%. We also make the modelling assumption that this increased power area density is achieved without changing the stack composition, which leads to a platinum loading of 0.12 g/kW and fuel cell stack power mass density of 2.44 kW/kg. These assumptions for future performance are in line with other literature values and are also explored in the sensitivity analysis in SI [61–63].

Our models for fuel cell Balance of Plant LCI (BoP) are also adopted from Simons and Bauer [61]. We assume that the current ancillary BoP (electrical components including DC/DC converter and controller) weighs 0.40 kg/kW and the essential BoP (components for management of air, water, fuel, and heat) weighs 0.33 kg/kW with a minimum mass of 10 kg. This weight is comparable to a 4 kW mobility-focused application sold by Intelligent Energy that weighs 22 kg [65]. We assume similar rates of improvements to BoP mass as for stack mass, with each of these assumed to reduce by 1.5% per year until 2030.

Fuel cell cost values are based on James et al. [66] and Wilson et al. [73]. We use a current manufacturing cost of 230 $/kW, which corresponds to an annual production volume on the order of 1000 fuel cells. In 2030, we expect cost to decrease to 60 $/kW, which reflects significant economies of scale in the manufacturing process as well as technological improvement. We examine the sensitivity of the results to fuel cell prices in SI, as there is very large uncertainty associated with these values.

2.6.6. Hydrogen tank

We assume that hydrogen is stored at 700 bar in an aluminum cylinder wrapped in carbon fiber with stainless steel fittings. We assume a storage efficiency of 5% hydrogen by weight in 2015, increasing to 7% in 2030, not including the mass of fixation devices and connections, which are assumed to weigh 5.5 kg. These assumptions are concurrent with values for currently available tanks as well as ultimate targets for hydrogen storage [75–78,84]. Manufacturing costs of hydrogen storage are based on the same sources and are assumed to amount to 25 $/kW h in 2015, decreasing to 17 $/kW h by 2030.

2.7. Motorcycle energy consumption

Motorcycle energy consumption is modelled using the methodology of Guzzela and Sciarretta [85], which was also implemented by Bauer and Hofer [42]. This methodology calculates wheel traction power demand given a velocity (v) versus time profile and assumptions about mass, vehicle area, coefficient of drag (C_d), air density (ρ), and rolling

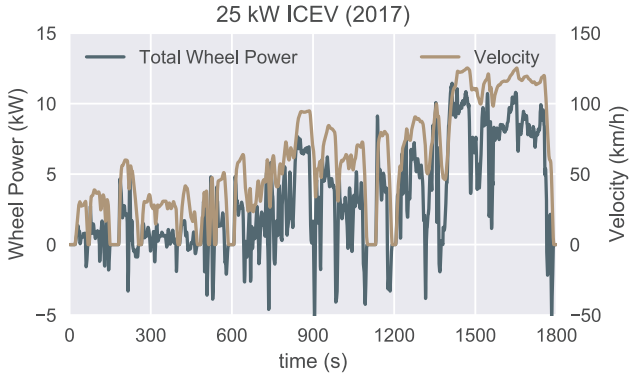

Fig. 2. World Harmonized Motorcycle Test Cycle (WMTC) velocity profile and calculated required wheel power for a 25 kW motorcycle. Negative wheel power means active braking.

resistance (C_r) according to the equation

$$Power_{wheel} = \left(\frac{v^2 Area C_d \rho}{2} + 9.81 mass C_r + mass\ a\dot{v}\right)v.$$

The velocity versus time profile used to calculate motorcycle energy consumption is taken from the World Harmonized Motorcycle Test Cycle [46]. Assumptions regarding input parameters are made based on literature values [86] for each of the motorcycle size classes. Smaller motorcycles are assumed to have larger aerodynamic resistances than larger motorcycles because of their more upright sitting position. These assumptions are listed in SI. A sample result for power demand at the wheel for a 25 kW ICEV motorcycle driving the WMTC is shown in Fig. 2 below. Motorcycle auxiliary power demand is small enough to be omitted in this analysis.

Energy recuperated during braking is also included for advanced powertrain motorcycles. However, because motorcycles do the majority of their braking with the front (non-drive) wheel, only 10% of braking energy is assumed to be recuperated, with this value improving to 15% in 2030. The resulting power demand at the wheel is then integrated over the length of the cycle to calculate the overall energy consumed at the wheel. The Tank to Wheel (TtW) energy consumption is then calculated by multiplying the wheel energy demand with the TtW efficiency for each motorcycle.

For ICEV motorcycles, the TtW efficiency is calibrated to be 14.5% in 2015, improving to 15.4% in 2030. This value considers the engine as well as the drivetrain and is estimated by comparing to available motorcycle fuel consumption literature values for different motorcycle sizes and production years (see SI). For BEV, the TtW efficiency is the product of the discharge efficiency of the battery (90% in 2015) and the efficiency of the electric motor and belt system (90% in 2015). BEV TtW efficiency is therefore assumed to be 81% in 2015, increasing to 83.5% in 2030. Furthermore, BEV energy consumption also considers charging losses from the grid with a charging efficiency of 90% in 2015 and 92% in 2030. FCEV share the same electric motor and belt system as BEV, but also have losses associated with the fuel cell system. Thus, FCEV TtW efficiency is 39.6% in 2015, increasing to 45.4% in 2030. As TtW efficiency is expected to have a very large impact on results, we include this parameter in the sensitivity analysis in SI.

This method allows a fair comparison of alternative drivetrains and can quite reasonably capture the impacts of vehicle size and future developments on energy consumption. One weakness of this method is that all vehicle types are assumed to be driven with the same acceleration rates, which can impact results. However, as can be seen in the results shown in SI, the majority of the energy demand at the wheel is due to air resistance and not acceleration, so this generalization is considered to be acceptable.

2.8. Motorcycle operating emissions

Operating exhaust emissions for conventional motorcycles are calculated for the WMTC velocity profile using the EMEP Tier 3 methodology up to and including Euro 3 for NO_x, CO, and NMVOC, and Tier 2 for PM 2.5 and NH_3 [52]. Euro emission limits for Euro 4 and Euro 5 are used until 2017 and 2020, respectively [9]. NMVOC also include evaporation emissions based on values from the HBEFA 3.3 [10]. Emissions are assumed to remain constant at the Euro 5 level after 2020. Fuel related emissions such as CO_2, SO_2, and metals are calculated using the EMEP 2014 emission factors per gram of fuel burned [52]. Road, tire and brake wear emissions are also included from the EMEP 2013 Tier 1 and 2 methodologies [52]. In order to account for the fact that heavier motorcycles will cause more particle emissions than smaller motorcycles, the lowest values in the EMEP ranges are considered to correspond to motorcycles with the lowest weight and the highest values to the largest weight, with the values in between being linearly interpolated. More information regarding operation emissions is available in SI.

2.9. Road production

Road production and maintenance inventories are taken directly from ecoinvent 3.2 and allocated based on gross vehicle mass kilometers.

2.10. Fuel and energy production

Gasoline datasets for two and four stroke motors are taken from ecoinvent 3.2. Electricity production from wind, solar, hydro, hard coal, nuclear, and natural gas combined cycle is included for German, Swiss or European average conditions where applicable. The current Swiss and European (ENTSO-E) electricity mixes are also included. Conversion from high to low voltage, transmission, and distribution of electricity are based on Swiss conditions in ecoinvent (see SI for more details).

Hydrogen production occurs either via Steam Reforming of Methane (SMR) or electrolysis with the electricity sources mentioned above. LCI datasets for hydrogen production are derived from Simons and Bauer [87], with efficiencies updated to 62% for electrolysis and 73% for SMR [88]. Hydrogen compression from 30 bar to 700 bar is assumed to require 1.82 kW h of electricity per kg hydrogen [88]. LCI datasets for hydrogen production are included in SI. We make the simplification that the LCI datasets for all energy carriers remain constant over time, as creating future electricity LCI datasets is considered to exceed the scope of this article.

Electricity and fossil fuel production costs are taken from Bauer and Hirschberg [67] with taxes and grid costs adopted from Hofer [89]. Hydrogen production costs are based on data from the US Department of Energy [88] using the industrial electricity and fossil fuel prices listed in Bauer and Hirschberg [67]. Gasoline costs increase from 0.16 $/kW h to 0.19 $/kW h (including taxes) from 2015 to 2030. Although SI includes many different electricity and hydrogen production pathways, we simplify this parameter in the main section of the paper: Electricity is assumed to come from the European average grid mix and cost private consumers 0.24 $/kW h, including the amortization of the charging station. Hydrogen is assumed to be produced by electrolysis with the same electricity source (electricity cost for industrial consumers 0.16 $/kW h) and cost 0.38 $/kW h in 2015 and 0.35 $/kW h in 2030 (see SI for further details and calculations). We assume no future changes to the current energy tax schemes.

2.11. Motorcycle end of life

As we use the recycled content approach system model of ecoinvent, the end of life treatment for components that are recycled usually

Fig. 3. Motorcycle mass breakdown.

contains a small amount of transportation and some energy requirements for dismantling components before their disposal or recycling. However, when compared to the impacts from the other phases of the life cycle, these impacts are generally negligible. Costs for motorcycle disposal are assumed to be equal to the value of the scrap and thus do not contribute to total ownership costs in any significant way.

3. Results and discussion

3.1. Motorcycle mass

Motorcycle mass is an important factor for riders because it strongly influences the handling and acceleration characteristics of a motorcycle. As can be seen in Fig. 3, FCEV and BEV motorcycles can already be built with masses similar to conventional motorcycles, though advanced powertrains are still heavier than conventional ones in the largest power categories. Overall system volume will also likely pose challenges for fuel cell motorcycle designers. Improved energy and power density of batteries and fuel cells are expected to significantly reduce the weight of advanced powertrain motorcycles in the future so that handling as well as power-to-weight ratios will become comparable for all powertrains. A comparison of model results with commercial motorcycle weights (in SI) shows that even FCEV and BEV have masses and power-to-weight ratios that are common among commercially available motorcycles.

3.2. Motorcycle final energy demand

Motorcycle final energy demand results are shown in Fig. 4. Larger motorcycles are found to have an energy demand two to three times higher than smaller motorcycles. Sensitivity analysis shows that this is only partially due to the fact that larger motorcycles are heavier and require more energy to accelerate. The main reason for this increased energy demand is that the WMTC assumes higher velocities for more powerful motorcycles, which significantly increases their aerodynamic losses. BEVs and FCEVs are found to have much lower energy consumption than ICEV motorcycles due to their higher TtW efficiencies. Recuperative braking does not result in significant energy savings. A reduction in motorcycle energy consumption over time is also found, though it is less pronounced than the differences between size categories and powertrain types. When modelling results for energy consumption are compared to values found in the literature (see SI), we find that our model captures trends in energy consumption versus both motorcycle size and production year. However, it should be mentioned that there is significant variation in the literature values and that there is limited literature information available for the energy consumption of electric motorcycles, though model results are found to be similar to energy consumption claims posted on manufacturer websites as well as the limited literature data available [11,19,20,29,31].

3.3. Motorcycle total ownership costs

Fig. 5 shows an overview of total ownership cost results. Results comparing motorcycle purchase costs as well as total ownership costs with different energy sources are included in SI. We find that mid-sized motorcycles have the lowest total ownership costs as they seem to strike a good balance between purchase and energy costs and higher annual travel distances. Smaller motorcycles are found to be dominated by capital costs, as their operational costs are low and total lifetime distances comparatively small. Sensitivity analysis shows that the total ownership costs of small motorcycles are cut nearly in half when the total lifetime distance travelled is doubled.

We find that current battery electric motorcycles have only marginally higher ownership costs compared to conventional motorcycles. This difference is well within the uncertainty of the input parameters, especially annual driving distance. As can be seen in the sensitivity

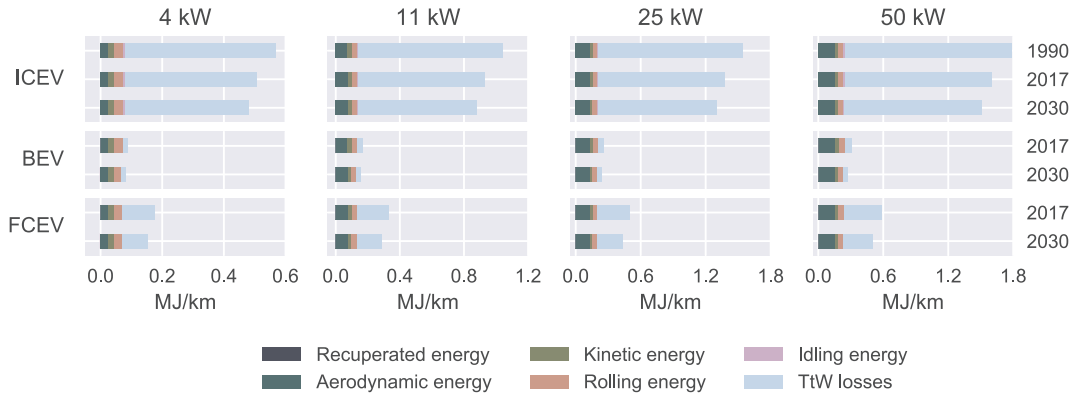

Fig. 4. Motorcycle Tank to Wheel energy consumption.

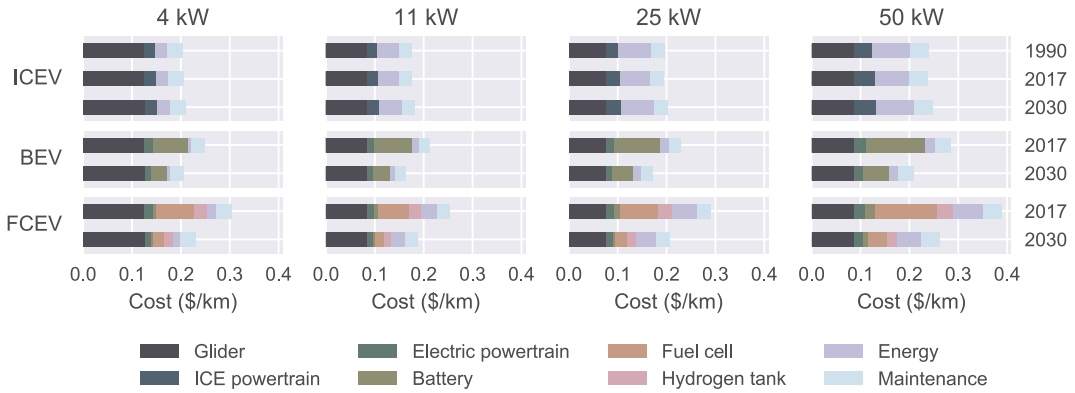

Fig. 5. Motorcycle total ownership costs, European average electricity.

analysis in SI, BEV are found to have lower ownership costs than ICEV when the annual distance travelled is increased.

While costs per kilometer for conventional motorcycles are expected to remain generally constant over time, very large cost reductions are calculated for advanced powertrain motorcycles. These are mostly due to expected improvements in lithium ion battery and PEM fuel cell technology, as well as improved cost performance due to large scale manufacturing of these novel technologies. It is likely that future BEV will have lower total ownership costs than ICEV.

We also find that even if fuel cell motorcycles were to be commercially produced with current fuel cell costs, they would not be cost competitive with BEV and ICEV. Next generation fuel cell motorcycles, if mass produced, are found to have the potential to be nearly competitive with other motorcycle types. However, uncertainties are very large as there are currently no commercially available fuel cell motorcycles based on which we could calibrate our modelling efforts, and future fuel cell costs are extremely dependent on the economies of scale reached when mass producing fuel cells, which is uncertain [62].

3.4. LCA results

Figs. 6 and 7 show a selection of life cycle impact assessment results. Fig. 6 shows results for the most common current energy carriers: gasoline for combustion motorcycles and electricity from the current average European mix for BEV and FCEV. Hydrogen is produced via electrolysis with the same electricity source. This figure includes four motorcycle sizes as well as past, current and future production years where applicable. Fig. 7 shows similar results, but for a wider range of energy chains with a focus on climate change impacts; complete results can be found in SI.

We first discuss results for ICEV and then compare the results for BEV and FCEV to this baseline. Climate Change (CC) impacts for current and future ICEV are dominated by tailpipe CO_2 emissions, though up to 30% of CC impacts from historical ICEV are due to carbon monoxide emissions on the order of 20 g/km. A further roughly 10% of CC impacts can be attributed to the upstream fuel production chain. Future CC improvements until 2030 are due nearly exclusively to incremental efficiency improvements. Particulate Matter Formation (PMF) results for current and future ICEV are dominated by the gasoline production chain for larger motorcycles and are rather equally spread out over the life cycle for smaller motorcycles. PMF results for historical motorcycles are dominated by tailpipe emissions: mostly NO_x for larger motorcycles and direct particulate emissions for smaller motorcycles, though current emission levels are low enough that they don't contribute significantly when considered over the entire life cycle. Photochemical Oxidant Formation (POF) results for ICEV are found to be dominated mostly by evaporation emissions for larger motorcycles, and tailpipe emissions of unburned hydrocarbons for smaller motorcycles. Improvements following tailpipe emission standards have been successful in greatly reducing these emissions, and future motorcycles are found to perform more than an order of magnitude better than historical motorcycles.

CC impacts for BEV are found to originate mostly from the production of the electricity used for recharging (especially for larger motorcycles) and the production of the battery (especially for smaller motorcycles). Impacts from future battery production are expected to decrease significantly in the future due to improvements in battery energy density. BEV charged with low carbon electricity are found to have extremely low life cycle CC impacts. Trends in results for PMF and POF are very similar to results for CC, as these impact categories are also dominated by the direct electricity consumption due to battery charging and the indirect electricity consumption of battery manufacture.

CC impacts from FCEV are found to be dominated by the hydrogen production chain, especially for larger motorcycles. This can mainly be attributed to the production of electrolyzer components which consume large amounts of copper and nickel, which in turn are associated with high SO_x emissions during the refining stage. For smaller motorcycles, the production of the motorcycle is also found to be very important, especially the production of the carbon fiber used in the hydrogen storage tank. When hydrogen is produced by electrolysis from wind electricity, the production of the hydrogen storage tank can be responsible for up to 50% of the total CC impacts. Although the energy storage density of hydrogen increases in the model until 2030 which will decrease tank size, the production of the hydrogen tank will still be important for small motorcycles in the future. It should be noted that we do not consider any changes to the processes used to produce carbon fiber in the future, which means that these impacts are likely to be overestimated if more efficient processes are developed. Roughly 50% of PMF and POF impacts from FCEV can be attributed to the hydrogen production chain and hydrogen tank production, with the remainder being due to various other processes.

When BEV and FCEV are powered by renewable energy, such as wind or hydro, they perform much better than ICEV, showing CC reductions of 60–80%. If the current European average electricity mix is used, BEV are still found to have 50–65% lower CC results, while savings for FCEV range from 15 to 30%. If electricity from coal is used as an energy source, BEV are still found to have lower CC impacts than ICEV by 20–30% while FCEV CC impacts are found to be higher than those due to ICEV (up to twice as high for current larger motorcycles and 40–50% higher for small motorcycles).

Performance in the POF category is clearly better for both BEV and FCEV compared to ICEV, even for future ICEV when exhaust and evaporation emissions are reduced and regardless of the source of electricity and hydrogen. Advanced powertrains are found to have a clear advantage in this category.

In the PMF category, all technologies perform similarly in current and future motorcycles, though historical ICEV motorcycles perform

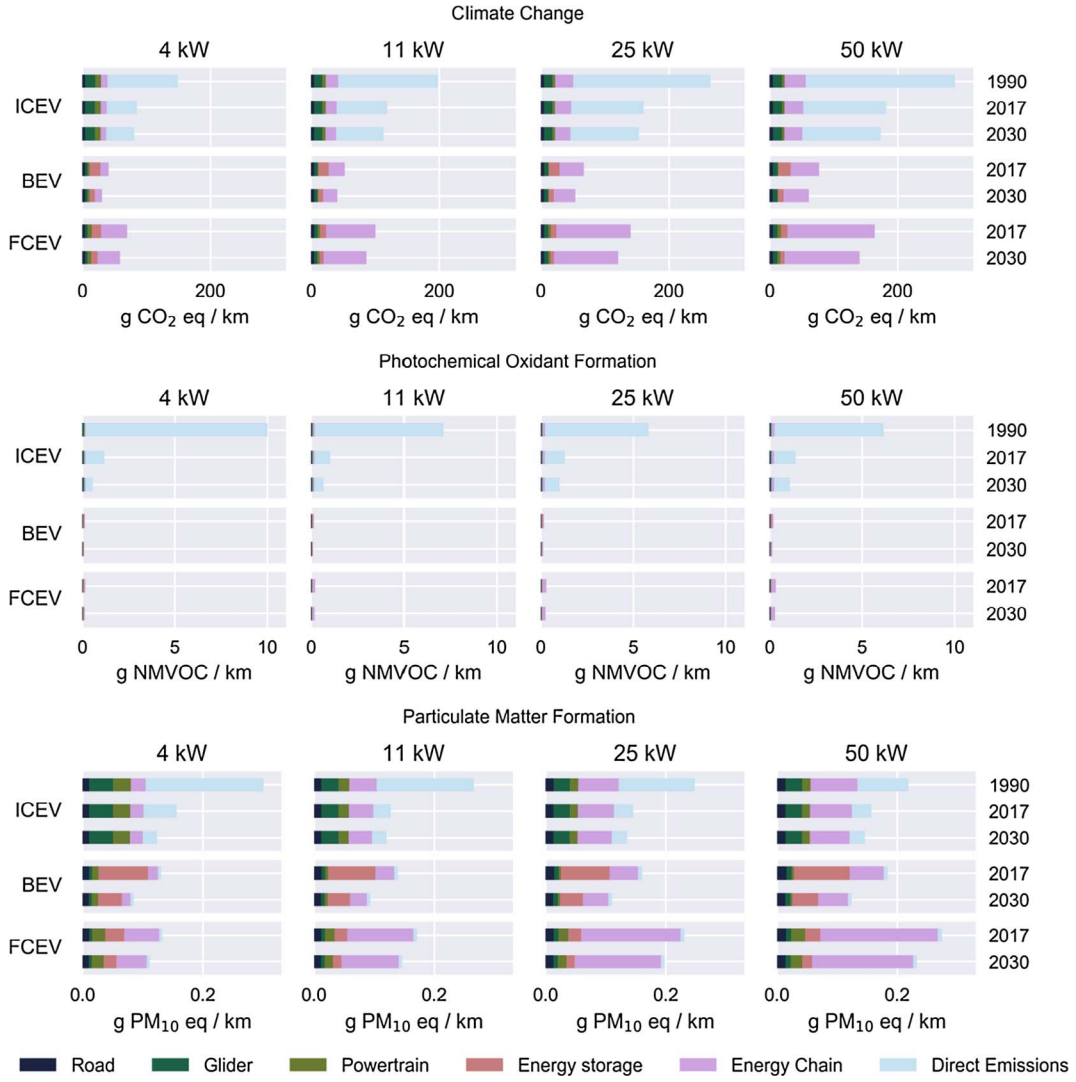

Fig. 6. Life cycle impact assessment results. Electricity source is the current European average mix; hydrogen source is electrolysis with the same electricity source.

much worse due to tailpipe emissions, and FCEV powered by hydrogen produced from coal electricity also perform rather poorly. Except for the improvements owing to increased powertrain energy efficiency, we find that particulate matter emissions from the fuel production chain for all powertrain types remain roughly constant until 2030. This is due to the use of a constant background LCI database to model the future energy chain. In reality, PM emissions from the energy chains are likely to decrease over time as electrolyzer efficiencies and lifetimes improve, mining emission standards become more strict, and fossil electricity related particulate matter emissions decrease. However, taking all these factors into account far exceeds the current scope. Furthermore, it is important to note that LCA counts all emissions equally, regardless of where they occur. For example, the emissions of SO_x due to ore refining in rural Russia receive the same burden per kilogram as SO_x emissions from motorcycles in a highly populated urban center. This must be kept in mind when comparing impacts in this category.

An examination of the complete list of recipe midpoint indicators in SI yields additional impact categories that are worth mentioning: BEV and FCEV are found to perform quite poorly in categories evaluating water and mineral depletion, with FCEV are also performing poorly with regard to ozone depletion.

3.5. Sensitivity analysis

As many of the input parameters are uncertain, we perform one-by-one sensitivity analysis to examine these parameters' impacts on the results. Sensitivity analysis results for variation in distance travelled, motorcycle size, range, TtW efficiency, driving cycle, number and weight of riders, battery and fuel cell prices, internal discount factor, aerodynamic resistance, and battery and fuel cell replacement parameters can be found in SI.

We find that CC results are particularly sensitive to the driving cycle, as the majority of the energy consumption is determined by motorcycle aerodynamic losses related to driving speed. Thus, variation among motorcycle size classes in energy consumption and CC impacts are more dependent on the type of driving than the size of the motorcycle: Urban driving has lower impacts than highway driving. BEV are less sensitive to this input parameter due to their higher TtW efficiencies. ICEV and FCEV are found to also be quite sensitive to variations in TtW efficiency, while BEV again appear to be less sensitive to this parameter. Environmental impacts are not found to be very sensitive to assumptions regarding fuel cell replacement, though they are sensitive to battery replacement assumptions, with a battery replacement during the lifecycle increasing GHG emissions by 10–20 g CO_2 eq/km.

Cost results are found to be sensitive to assumptions related to

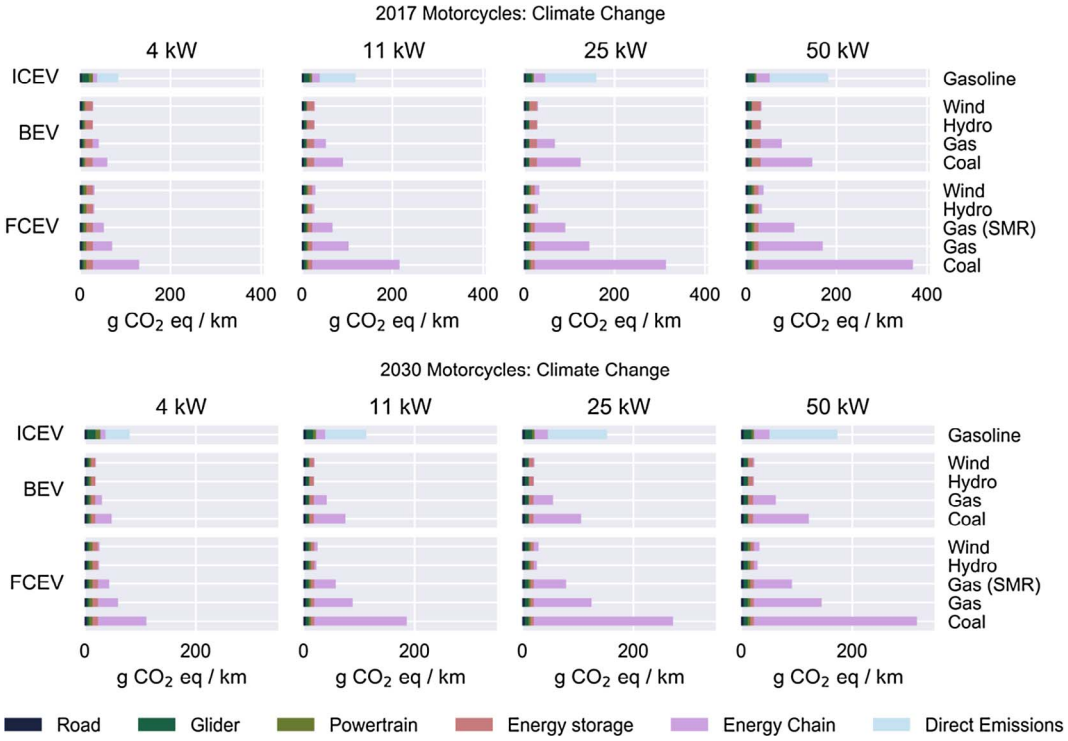

Fig. 7. Life cycle impact assessment (climate change) results for a variety of energy chains for 2017 and 2030 motorcycles. For FCEV, the hydrogen is assumed to be produced by steam reforming of methane in the Gas (SMR) case and electrolysis in all others.

amortized purchase costs, such as annual distance travelled and internal discount rates. Range and other assumptions regarding battery purchase are important for BEV while parameters determining fuel cell size and production costs are important for FCEV. Cost results are rather insensitive to TtW efficiency.

The comparative ranking of motorcycle sizes and powertrain technologies did not change significantly for nearly all sensitivity analysis parameters examined.

For each powertrain, the results are most sensitive to the following parameters: (ICEV) TtW efficiency, CO, NOx, PM, and unburned hydrocarbon emissions, motorcycle lifetime. (BEV) Source of electricity for battery charging, battery energy density, battery production electricity demand, battery cost, battery lifetime, motorcycle lifetime. (FCEV) Source of hydrogen, fuel cell efficiency, fuel cell lifetime, motorcycle lifetime.

3.6. Limitations and uncertainties

There are several important limitations and sources of uncertainty in this study. The main limitation in the study is an issue encountered by nearly all prospective LCA studies [90]: the fact that current life cycle inventories are used in future background LCA processes. Another limitation is that the impact assessment is not location specific, which is important for local air pollution indicators such as POF and PMF. Furthermore, noise pollution, which is an important impact on human health caused by urban transportation, is not included as the corresponding methodology is not yet in place for LCA.

There is a high degree of uncertainty regarding the trends used to model future motorcycle performance and costs. Particularly the assumptions about the future development of batteries energy density and fuel cell efficiency and costs are significant sources of uncertainty that are important for results. We have addressed these uncertainties in the sensitivity analysis in SI and encourage the reader to examine them in more detail. Finally, the variations between individual motorcycles within each size and powertrain class and variation in driving style can be very large, though the model considers only one average motorcycle with average driving patterns in each class.

4. Conclusions

In this study, we develop life cycle inventories and calculate total ownership costs for internal combustion engine (ICEV), battery electric (BEV) and fuel cell electric (FCEV) motorcycles for four common motorcycle size categories. We consider not only current technologies, but also include the likely near future development of key parameters in order to estimate and compare the performance of motorcycles that may be available in 2030.

We find that environmental impacts per kilometer are much lower for urban driving than highway driving, a distinction that is more important than variations in motorcycle power. Furthermore, we find that battery electric motorcycles are able to offer significant reductions in climate change contributions compared to conventional motorcycles with similar total ownership costs per kilometer. Even when BEV are charged with electricity from fossil fuels, such as coal or natural gas, they have lower climate change impacts than conventional motorcycles. The main drawback of BEV is their reduced range capability, though this is presumably less significant for urban driving. We find that future fuel cell electric motorcycles will likely also offer climate change benefits compared to conventional motorcycles, providing the hydrogen used originates from low carbon sources. However, the total future ownership costs of fuel cell motorcycles remain highly uncertain and are unlikely to be lower than those of battery electric or conventional motorcycles even with greatly reduced fuel cell production costs.

In order to aid future research on the environmental impacts of motorcycles and passenger transportation, we have included our complete results and calculations in SI. This includes all motorcycle production years from 1990 to 2030 for four motorcycle size classes, three powertrains (where applicable), and a variety of common energy chains.

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Appendix A. Supplementary material

The SI for this body of work includes complete results in the file *Motorcycle results.xlsx*. This comprises all motorcycle characterization values in one sheet and life cycle impact assessment results for all ReCiPe 2008 midpoint and endpoint categories in another, shown separately for each foreground process.

Furthermore, we include jupyter notebooks that readers can use to recalculate results and change input parameters. For readers who are not familiar with jupyter notebooks, we have also included the same file in an HTML format where the calculation procedure can be followed and results viewed, but not modified.

In order to run the calculation file, several input files are required. *Fuel cell.xlsx* contains the LCI for fuel cell production from Simons and Bauer [61], *Battery.xlsx* contains the LCI for the lithium ion battery production from Ellingsen and Majeau-Bettez [81], and *Motorcycle Energy Sources.xlsx* contains energy chain calculation inputs and LCI data that can be read with brightway2 [91]. *Input data.xlsx* contains all other input values needed for the calculation to run. Supplementary data associated with this article can be found, in the online version, at http://dx.doi.org/10.1016/j.apenergy.2017.12.100.

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Glossary

BEV: battery electric vehicle
BoP: balance of plant
CC: climate change
FCEV: fuel cell electric vehicle
GHG: greenhouse gas
GWP: global warming potential
ICE: internal combustion engine
ICEV: internal combustion engine vehicle
LCA: life cycle assessment
LCI: life cycle inventory
LCIA: life cycle impact assessment
NMVOC: non methane volatile organic compounds
PEM: proton exchange membrane
PM: particulate matter
PMF: particulate matter formation
POF: photochemical oxidant formation
SMR: steam reforming of methane
TtW: tank to wheel
WMTC: world harmonized motorcycle test cycle